NEW METHODS FOR MEASURING PERFORMANCE OF MONOLITHIC MULTI-JUNCTION SOLAR CELLS

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ABSTRACT

The commercialization of multi-junction solar cells for both space and terrestrial applications has increased the need to accurately determine cell performance using typical solar simulators and test equipment. This paper describes specific test methods recently applied in characterizing the performance of both tandem and triple-junction solar cells. Methods applied included: current-voltage measurements in forward and reverse bias using a xenon-arc solar simulator, absolute spectral response measurements of separate junctions using both light and voltage bias, a device simulation model, and a spectral mismatch calculation procedure tailored to multi-junction cells. Procedures are illustrated using measurements for GaInP/GaAs tandem cells, GaInP/GaAs/Ge triple-junction cells, and Ge cells supplied by different manufacturers.

INTRODUCTION

The high performance potential of multi-junction solar cells has been recognized for over 30 years [1]. Today, the reality is that several U.S. manufacturers have highly efficient multi-junction solar cells in production, primarily for space power applications [2, 3]. These high efficiency devices are also being seriously considered for terrestrial applications as well [4, 5]. Unfortunately, along with the high performance has come device complexity. This device complexity is not as evident in the actual application of the multi-junction cells as it is when conducting detailed performance testing in the laboratory. The complexity stems primarily from the cells having only two "terminals," meaning the separate junctions cannot be tested independently. Nonetheless, detailed performance testing can't be avoided; it is required both for optimizing cell manufacturing procedures and for modeling the performance of systems using the cell technology. Other researchers have also documented their efforts to characterize multi-junction solar cells [6, 7, 8, 9], and a standardized test procedure is currently under development [10]. The purpose of this paper is to illustrate and document new test procedures we've found effective in characterizing the performance of recently manufactured multi-junction cells.

SIMULATION OF MULTI-JUNCTION CELLS

Numerical simulation (modeling) of a multi-junction cell helps clarify the interactive influences of the current-voltage (I-V) characteristics of individual junctions on the I-V curve for the composite cell. A simulation code called PVSIM was used to interpret the behavior of monolithic, two-terminal, multi-junction cells [11]. PVSIM uses a two-diode equivalent circuit with shunt and series resistance components to simulate the behavior of each junction. The model also includes parameters to simulate the reverse-voltage (2nd quadrant) "breakdown" of each junction. Figure 1 illustrates both the simulation and the measured I-V characteristics (1st quadrant only) of a triple-junction GaInP/GaAs/Ge solar cell for a one-sun AM1.5 standard solar spectrum. The "composite" I-V curve in the figure is simply the summation of the voltage produced by each junction at a given current level. For this case, the solar simulator provided a spectrum that closely matched the standard spectrum, so the short-circuit current (I_{sc}) values for the separate junctions mimic the situation for the standard reporting condition. The reverse breakdown voltages for all three junctions were determined from other tests. The top GaInP junction limited the I_{sc} of the multi-junction cell, and the reverse voltage characteristics of the other two junctions did not influence the shape of the composite I-V curve in the 1st quadrant.

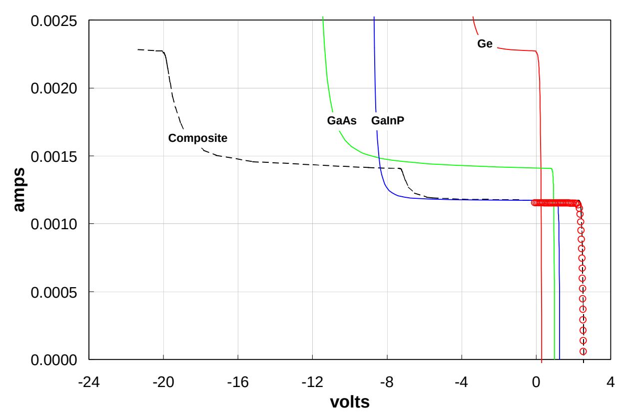

Fig. 1. Measured (open circular symbols) and simulated one-sun I-V for triple-junction cell under ASTM AM1.5 standard spectrum.

Figure 2 illustrates a situation where the solar simulator didn't match the ASTM standard solar spectrum and had inadequate long-wavelength light for the bottom Ge junction. In this case, the Ge junction limited the I_{sc} of the cell and its reverse voltage characteristics dramatically altered the shape of the composite I-V curve. Without a simulation model or an understanding of the reverse-voltage characteristics of each junction, it is difficult to determine performance at standard reporting conditions starting with a measured I-V curve as shown in Figure 2.

This situation may also be of practical importance for concentrator modules developed to use high performance GaInP/GaAs/Ge cells. The optical material (acrylic) used for concentrating Fresnel lenses has relatively low transmittance at wavelengths greater than 1200 nm, which will significantly reduce the I_{sc} of the Ge junction, however, probably not to the extent illustrated in Figure 2. In addition, as documented elsewhere, special attention will need to be paid to the refractive characteristics of the facets on Fresnel lenses [12]. Otherwise, multi-junction cell performance may be significantly limited by chromatic aberration in the lens which could produce a highly non-uniform distribution of the influential wavelengths of light for each separate junction. Non-uniform illumination of the separate junctions results in performance losses due to the emitter sheet resistance.

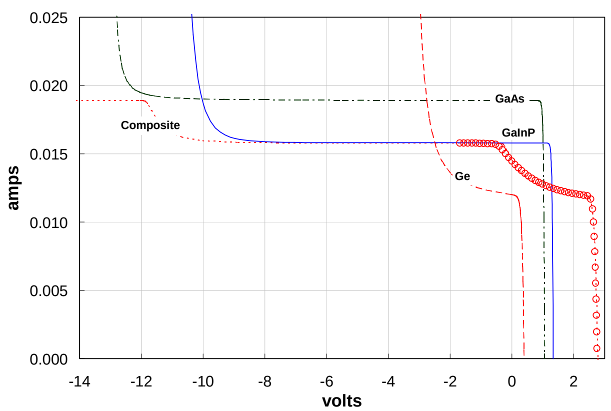

Fig. 2. Measured (open circular symbols) and simulated I-V curve at 12X concentration using solar simulator with inadequate long-wavelength light for Ge junction.

SPECTRAL RESPONSE MEASUREMENTS

In order to properly determine the performance of a multi-junction cell at standard reporting conditions, a method for determining the relative short-circuit currents of the separate junctions is required. The most commonly used approach is to measure spectral response. Spectral response is typically defined as the current density (A/cm^2) produced per monochromatic power (W/cm^2) incident on the cell at a voltage bias of zero volts (short circuit). Achieving this specific condition for the separate junctions in a multi-junction cell can be difficult. Spectral response measurements must provide either "absolute" spectral response or a direct relative comparison between the separate junctions. Numerically convolving the desired (standard) solar spectrum with the spectral response measurements provides relative short-circuit current densities (J_{sc}) for the separate junctions. Figure 3 illustrates successful measurement of the absolute spectral response for the separate junctions in a GaInP/GaAs/Ge triple-junction cell. The irregular response of the Ge junction was the result of optical interference in the very thin GaInP and GaAs epitaxial layers. Absolute spectral response measurements, when coupled with spectral reflectance measurements, also provides a means for calculating the internal quantum efficiency (IQE) for each junction. IQE provides valuable information for optimization of manufacturing procedures.

Measurement Equipment

The spectral response measurement equipment at Sandia uses an Oriel quartz-tungsten-halogen light source, a Digichrom Model 240 monochromator, a light-beam chopper, a Stanford Research lock-in amplifier, and a Stanford Research preamplifier, to provide cell response over a spot-size of about 16 mm^2. The lock-in amplifier distinguishes between cell response due to pulsed (chopped) monochromatic illumination and steady response due to a continuous light bias. The preamplifier improves measurement accuracy at low response levels and also provides a current-limiting feature (5 mA) that tends to protect cells that may be sensitive to current transients. Reference detectors calibrated by the National Institute of Standards and Technology (NIST) provide absolute calibration of the monochromatic beam of light. Cells are mounted on a temperature-controlled vacuum fixture during testing. For the cells described in this paper, we used a combination of Oriel optical filters (band-pass and long-pass), and variable intensity lasers to "light bias" the separate junctions. A 532-nm diode-laser was used to bias the GaInP junction, an 832-nm diode-laser the GaAs junction, and a 1064-nm YaG laser the Ge junction. The wavelength range for the light biases must be tailored to the bandgap and spectral response characteristics of the separate junctions in a multi-junction cell. In general, optical filters with desired transmittance characteristics over a wide wavelength range (300 to 1800 nm) can be difficult to find. We've found that variable intensity lasers often provide the best alternative for light biasing.

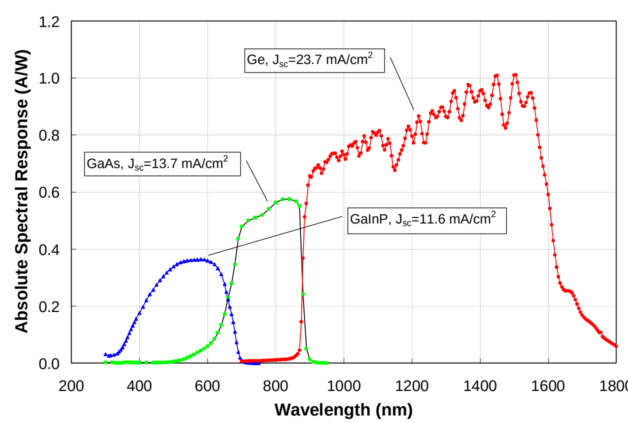

Fig. 3. Absolute spectral response of separate junctions in a high-performance two-terminal GaInP/GaAs/Ge triple-junction solar cell.

Measurement Procedure

For series-connected junctions that are illuminated by the standard solar spectrum, the junction with the lowest I_{sc} is typically assumed to limit the short-circuit current of the composite cell to a value equivalent to its own short-circuit current. However, this assumption is only valid for ideal situations where individual junctions don't have shunt-resistance or reverse-breakdown characteristics that alter the shape of the composite I-V curve in the 1st quadrant ($V \geq 0$). Figure 4 illustrates a measured I-V curve for an individual 1-cm^2 Ge cell, and also the measured "composite" I-V curve with the Ge cell electrically interconnected in series with a 4-cm^2 GaInP/GaAs tandem -junction cell. For this special case, the I_{sc} of the Ge cell was lower than the tandem-junction cell because of its smaller area. The measured curves illustrate how the reverse breakdown of the Ge cell dramatically influenced the shape of the composite I-V curve in a manner similar to that previously shown in Figure 2. The reverse breakdown voltage for a variety of Ge junctions was found to be in the range from -1 to -5 V. The implication of this discussion for spectral response measurements is that a combination of light- and voltage-bias must be found that provides an appropriate "short-circuit condition" for the junction of interest. For the series-connected situation in Figure 4, a forward bias of 2.2 volts would be required to establish an appropriate situation for measuring the spectral response of the Ge junction.

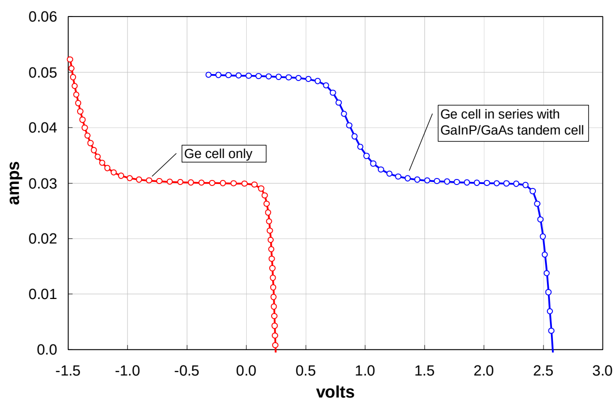

Fig. 4. Measured I-V curve for an individual Ge cell and for the composite I-V curve with the Ge cell in series with a GaInP/GaAs tandem cell.

Figure 5 illustrates a simulated condition for the separate junctions in a triple-junction cell. This simulation represents a situation where the top two junctions (GaInP and GaAs) were light biased with continuous (dc) laser illumination and a pulsed (chopped) monochromatic illumination was used to measure the spectral response of the bottom Ge junction. The lock-in amplifier associated with the measurement system separates the response due to the chopped monochromatic light from the steady laser illumination used as a light bias. The "composite" curve in the figure represents the steady or "dc" response from the two-terminal triple junction cell as a function of voltage, and as if the pulsed monochromatic light was on continuously. It can be seen from the figure that in order to reach a point on the composite I-V curve representative of the short-circuit condition for the Ge junction a forward voltage bias of about 2.2 V is required. Another unfortunate observation from these simulations is that a near infinite number of combinations of light bias, voltage bias, and monochromatic wavelength are possible, thus complicating the measurement process. However, a procedure has been found that makes the measurement process manageable. This process involves minimizing unwanted contributions to spectral response from the junctions not being characterized.

For instance, when measuring spectral response for the Ge junction, there should be no response at 550 nm since that wavelength is absorbed by the top GaInP junction. However, if there is response at 550 nm, a situation similar to Figure 5 exists. At 550-nm, no current is being generated in the Ge junction so its I-V curve would be shifted down to $I_{sc}=0$ which results in the composite I-V curve also shifting down and to the left. Note that this shifting would result in a situation at V=0 where the top GaInP junction was contributing current to the spectral response measurement at 550 nm, erroneously suggesting that the Ge junction was responding at that wavelength. This situation can be corrected by adding a forward voltage bias across the multi-junction cell. Increasing the voltage bias will minimize any unwanted contribution from the GaInP junction. A similar argument can be made concerning unwanted contribution from the GaAs junction at a wavelength of 800 nm.

Thus, a reasonably straight forward procedure to use when measuring the spectral response of the Ge junction is to apply adequate light bias to the GaInP and GaAs junctions and then increase the voltage bias to minimize the measured spectral response at 550 nm and at 800 nm. Minimizing the unwanted contributions from the GaInP and GaAs junctions tends to maximize the response from the Ge junction and provides the "correct" spectral response. The simulation in Figure 5 also suggests that voltage bias would not be necessary to measure the spectral response of the Ge junction if its reverse breakdown voltage was significantly larger in magnitude than the composite voltage of the multi-junction cell.

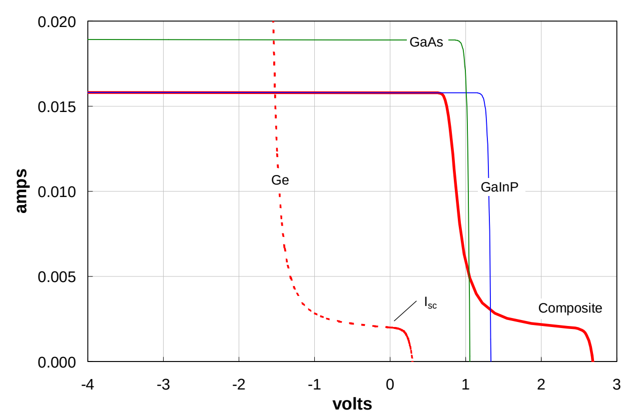

Fig. 5. Simulated I-V characteristics for spectral response measurement of the Ge junction in a triple-junction cell at a wavelength of 1000-nm. GaInP and GaAs junctions are continuously light-biased and a pulsed (chopped) monochromatic beam used to illuminate Ge.

Validation of Procedure

In order to better understand the combination of voltage-bias and light-bias levels required for spectral response measurements, the same experimental (two component) multi-junction cell measured in Figure 4 was used. The Ge cell in this case had electrically inactive "window" layers of GaInP and GaAs epitaxially deposited on its top surface, thus mimicking the optical characteristics in a monolithic GaInP/GaAs/Ge device. For this unique situation, the spectral response of the Ge cell could be independently measured, and its spectral response could also be measured when electrically connected in series with the GaInP/GaAs tandem cell. Validation of our spectral response measurement procedure for multi-junction cells, with both light and voltage bias, was achieved when spectral response measurements for the series-connected Ge cell matched those obtained for the Ge cell by itself. Figure 6 shows spectral response measurements for the Ge junction in the experimental device, for different combinations of light-bias on the top two junctions and voltage-bias across all three junctions. When the appropriate combination of light-bias and voltage-bias were achieved, the unwanted current generation at 550 and 800 nm was minimized, and the correct result for the Ge junction was achieved.

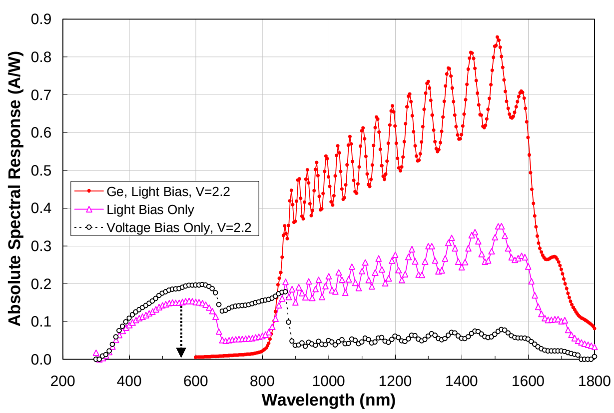

Fig. 6. Measurements illustrating the influence of light and voltage bias on the response measured for the bottom Ge junction in a GaInP/GaAs/Ge cell.

SOLAR SIMULATOR SPECTRUM VERSUS DESIRED STANDARD SPECTRUM

The spectral irradiance provided by solar simulators never exactly matches the solar spectral distributions established as standards for different air mass conditions (AM1.5 or AM0), particularly for multi-junction cells where spectral response may span the wavelength range from 300 to 1800 nm. A few multiple-light-source simulators have been developed to minimize this problem but they are complex and expensive. In any case, when using simulators to measure the performance of multi-junction cells, it is necessary to apply multiple spectral mismatch corrections [13]. However, simply calculating the spectral mismatch correction for the junction limiting the I_{sc} during measurement and then applying that correction to the measured I-V curve is not a valid approach. Figure 2 previously illustrated an extreme example. A calculated spectral correction for the Ge junction would suggest that the measured I-V curve needs to almost double in current for the standard spectrum, clearly unrealistic because the top (GaInP) junction would limit the multi-junction cell's I_{sc} after the Ge junction is increased by about 10% in current.

A more valid approach for multi-junction cells is to calculate mismatch corrections for each junction, M_i, and calculate J_{sc} ratios relative to the junction limiting the I_{sc} during I-V measurements. Ideally, the simulator spectrum can be altered such that the same junction limits I_{sc} for both the simulator and the standard solar spectrum. The J_{sc} ratios are calculated using a numerical integration of the absolute spectral response measurements and the measured spectral irradiance of the solar simulator. This procedure is expressed by Equations 1 through 5, and provides the corrected short-circuit current, I_{sco}, for the multi-junction cell at standard reporting conditions (SRC). This approach is valid for well-behaved multi-junction cell characteristics such as illustrated in Figure 1, but cannot be applied without additional consideration for situations such as illustrated in Figure 2.

$$I_{scm} = I_{sc1} \quad \text{(Measured } I_{sc} \text{ for limiting junction.)} \quad (1)$$

$$I_{sco1} = \frac{I_{sc1}}{M_1} \quad \text{(Limiting junction at SRC.)} \quad (2)$$

$$I_{sco2} = \frac{J_{sc2}}{J_{sc1}} \cdot \frac{I_{sc1}}{M_2} \quad \text{(Second junction at SRC.)} \quad (3)$$

$$I_{sco3} = \frac{J_{sc3}}{J_{sc1}} \cdot \frac{I_{sc1}}{M_3} \quad \text{(Third junction at SRC.)} \quad (4)$$

$$I_{sco} = MIN\left[I_{sco1}, I_{sco2}, I_{sco3}\right] \quad \text{(Device } I_{sc} \text{ at SRC)} \quad (5)$$

REVERSE VOLTAGE MEASUREMENTS

There is an alternative method to complex spectral response measurements for determining relative short-circuit currents for the separate junctions in a multi-junction cell. The method is straightforward, however, the potential for cell damage is involved if any one of the junctions in the cell is intolerant of operation in reverse bias. The manufacturer should be able to tell you if their cells will tolerate reverse bias measurements.

When illuminated by a light source closely simulating the standard solar spectrum, reverse voltage I-V measurements for multi-junction cells can provide valuable insight for interpreting both performance and spectral response measurements. For reverse voltages (2^{nd} quadrant), junction shunt resistance and junction breakdown characteristics dictate the shape of the I-V curve. As an example, Figure 7 illustrates measurement of the reverse voltage characteristics for a GaInP/GaAs/Ge triple-junction cell. Note that this measured behavior closely mimics the simulation for the composite I-V curve previously shown in Figure 1. The relative short-circuit currents for the three separate junctions are directly indicated by the three "plateaus" observed. The inflections in the curve indicate the onset of reverse breakdown in the junctions indicated. I_{sc} ratios relative to the GaInP junction can be calculated for the other two junctions by using the I_{sc} measured for the GaInP as the divisor. These I_{sc} ratios can be used for two purposes. They can be used to scale spectral response measurements for separate junctions if the spectral response measurement procedure does not provide absolute values directly. The I_{sc} ratios can also be used instead of J_{sc} ratios in Equations 3 and 4 to determine the appropriate spectral mismatch correction.

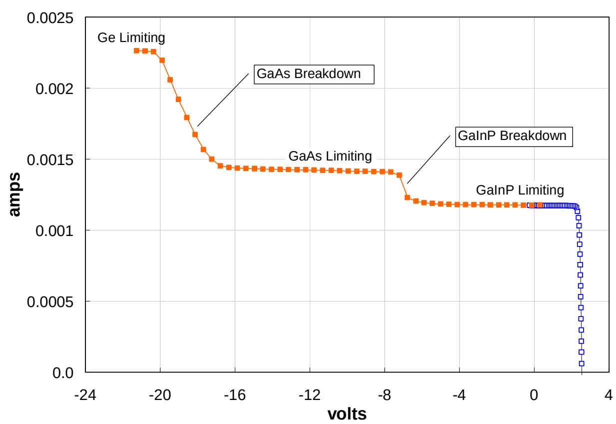

Fig. 7. Reverse-voltage one-sun I-V measurement for GaInP/GaAs/Ge triple-junction cell showing breakdown and current-limiting plateaus for separate junctions.

CONCLUSIONS

Test procedures have been demonstrated that should assist manufacturers in the development of multi-junction solar cells, and also contribute to the development of standardized test procedures for these devices.

Junctions with non-ideal reverse bias characteristics can dramatically alter the forward bias I-V characteristics of a multi-junction solar cell. This effect can influence both performance and spectral response measurements for current GaInP/GaAs/Ge triple-junction cells under certain illumination conditions. Therefore, a test procedure using a combination of light bias and voltage bias is often needed to obtain absolute spectral response. Such a procedure for spectral response measurements was presented with experimental validation.

A procedure for applying spectral mismatch corrections for multi-junction performance measurements has also been developed. This procedure assists in determining the correct I_{sc} at standard reporting conditions when measurements are made using solar simulators.

Finally, an alternative approach for determining the relative short-circuit currents for the separate junctions in a multi-junction cell has been presented. This technique uses reverse-bias I-V analysis and can be used to complement, or as an alternative to, spectral response measurements for the separate junctions.

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